



WESTERN WATER ASSESSMENT

A NOAA RISA TEAM

2010 – 2016 Final Report



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Introduction

The mission of Western Water Assessment (WWA) during the 2010-2016 grant was to identify and characterize regional vulnerabilities to and impacts of climate variability and change, and to develop information, products and processes to assist decision makers throughout the Intermountain West. Using multidisciplinary teams of experts in climate, hydrology, ecology, law, and policy, WWA worked with decision makers across our three states, Colorado, Utah and Wyoming, to produce policy-relevant information about climate variability and change. By building relationships and networks of decision makers, our team developed practical research programs and useful information products. WWA, a NOAA Regional Integrated Sciences and Assessment program (RISA), is formally part of the Cooperative Institute for Research in Environmental Sciences (CIRES) at the University of Colorado in Boulder. Our researchers and partners come from universities and federal institutions in Colorado, Wyoming, and Utah. Table 1 lists those who were a part of the WWA team at some point during the grant period of 2010 to 2016.

This final report covers the research, outreach, products and partnerships of the 2010-2015 WWA grant plus one year of a no-cost extension to August 2016. While this report contains a summary of the work done by many people over those years, we are not able to include every detail. More information can be found in the annual reports of the individual years of this grant, which are located on our website: <http://www.colorado.edu/about/reports/>.

Team Members

Table 1. Western Water Assessment Research Team

Team Member	Title	Expertise
Andersson, Krister	Assistant Professor, Political Science, Univ. of Colorado	Environmental governance
Archie, Kellie	Graduate Research Assistant, Univ. of Colorado	Climate adaptation
Seth Arens	Utah Research Integration Specialist	Eco-hydrology, air quality
Averyt, Kristen	Associate Director for Science, CIRES	Climatology, energy-water, assessment processes
Bardsley, Tim	Utah Liaison, Western Water Assessment	Snow hydrology, climate vulnerability in water utilities
Barsugli, Joseph	Research Scientist, CIRES, Univ. of Colorado	Climate dynamics
Berggren, John	Graduate Research Assistant, Univ. of Colorado	Climate adaptation, water policy
Bracken, Cameron	Graduate Research Assistant, Univ. of Colorado	Water resources engineering
Buma, Brian	Graduate Research Assistant, Univ. of Colorado	Remote sensing, landscape ecology
Clifford, Katie	Graduate Research Assistant, Univ. of Colorado	Conservation decision making
Cody, Kelsey	Graduate Research Assistant, Univ. of Colorado	Water policy
Cordalis, Daniel	Graduate Research Assistant, Univ. of Colorado	Tribal policy and law
Cozzetto, Karen	Postdoctoral Research Associate, CIRES, Univ. of Colorado	Hydroclimatology, surface water hydrology and ecology, climate adaptation
Deems, Jeff	Research Scientist, CIRES, Univ. of Colorado	Climate and snow modeling
Dilling, Lisa	Director, Western Water Assessment Assistant Professor, Environmental Studies, Univ. of Colorado	Climate information and decision making
Duren, Sabre	Graduate Research Assistant, Univ. of Colorado	Tribal and environmental policy
Endter-Wada, Joanna	Associate Professor, Environment & Society, Utah State Univ.	Human dimensions of ecosystem science and

Team Member	Title	Expertise
		management
Gillies, Robert	Utah State Climatologist, Utah State Univ.	Climatology
Gordon, Eric	Managing Director, Western Water Assessment (until 8/2015)	Climate adaptation
Gray, Stephen	Wyoming State Climatologist, Univ. of Wyoming	Climatology and paleoclimatology
Guentchev, Galina	Postdoctoral Research Associate, University Corporation for Atmospheric Research (UCAR), CLIVAR, Postdocs Apply Climate Expertise (PACE)	Climate dynamics
Huisenga, Mary	Professional Research Assistant, Univ. of Colorado	Limnology, decision modeling
Kasprzyk, Joseph	Assistant Professor, Civil Engineering, Univ. of Colorado	Multi-objective analysis for water management
Kenney, Douglas	Director, Western Water Policy Program, Getches-Wilkinson Center for Natural Resources, Energy, and the Environment, Univ. of Colorado School of Law	Western water policy and law
Klein, Roberta	Managing Director, Center for Science and Technology Policy Research, Univ. of Colorado	Environmental policy
Livneh, Ben	Research Scientist, CIRES, Univ. of Colorado	Hydrologic modeling
Lukas, Jeffrey	Senior Research Associate, Western Water Assessment	Paleohydrology, forest ecology
Mahoney, Kelly	Research Scientist, CIRES, Univ. of Colorado	Hydrometeorology, extreme precipitation
McCurdy, Adam	Graduate Research Assistant, Univ. of Colorado	Climate risk assessment
McCutchan, James	Associate Director, Center for Limnology, CIRES, Univ. of Colorado	Limnology
McNie, Elizabeth	Research Scientist, CIRES, Univ. of Colorado	Science policy, program evaluation
Meldrum, James	Research Associate, Institute for Behavioral Studies, Univ. of Colorado	Applied environmental economics
Miller, Scott	Associate Professor, Renewable Resources, Univ. of Wyoming	Spatial processes in watershed hydrology
Molotch, Noah	Assistant Professor, Dept. of Geography, Univ. of Colorado	Snow hydrology
Nania, Julie	Research Assistant, Getches-Wilkinson Center for Energy, Natural Resources, and the Environment, Univ. of Colorado School of Law	Tribal law
Neff, Jason	Associate Professor, Geological Sciences and Environmental Studies, Univ. of Colorado	Biogeochemistry
Nowak, Kenneth	Graduate Research Assistant, Univ. of Colorado	Water resources engineering
Painter, Thomas	Research Scientist, NASA Jet Propulsion Laboratory, California Institute of Technology	Hydrology
Rangwala, Imtiaz	Research Scientist, CIRES, Univ. of Colorado	Regional climate change, high elevation climate
Rajagopalan, Balaji	Professor, Civil Engineering, Univ. of Colorado	Water resources engineering
Ray, Andrea	Scientist, Climate Analysis Branch, NOAA ESRL Physical Sciences Division	Climate-society interactions, water management
Rice, Janine	WWA Postdoctoral Research Associate, CIRES, Univ. of Colorado	Climate impacts and adaptation in National Forests
Rick, Ursula	Program Manager, Western Water Assessment (begin 9/2015)	Science policy, glacial hydrology
Rosenberg, David	Assistant Professor, Civil and Environmental Engineering, Utah State Univ.	Water resources engineering
Schneider, Dominik	Graduate Research Assistant, Univ. of Colorado	Snow hydrology
Smith, Rebecca	Graduate Research Assistant, Univ. of Colorado	Multi-objective analysis for water management
Squillace, Mark	Director, NRLC, Univ. of Colorado	Natural resources and water law

Team Member	Title	Expertise
Teel-Simmonds, Julie	Senior Research Associate, Center for Energy and Environmental Security, Univ. of Colorado	Energy law; climate policy; tribal climate adaptation
Travis, William	Associate Professor, Geography, Univ. of Colorado	Natural hazards, climate impacts and adaptation
Udall, Bradley	Senior Fellow, Getches-Wilkinson Center for Natural Resources, Energy, and the Environment, Univ. of Colorado School of Law	Colorado River, hydrology, policy
van Drunick, Suzanne	Assistant Director for Science, CIRES, Univ. of Colorado	Hydrology and ecology
Verdin, Andrew	Graduate Research Assistant, Univ. of Colorado	Water resources engineering
Wade, Lisa	Graduate Research Assistant, Univ. of Colorado	Water resources engineering
Wessman, Carol	Professor, Ecology and Evolutionary Biology, Univ. of Colorado	Landscape ecology, remote sensing
West, Nicholas	Graduate Research Assistant, Univ. of Colorado	Tribal policy and law
Wolter, Klaus	Research Scientist, CIRES, Univ. of Colorado	Climatology and meteorology
Zagona, Edith	Director, Center for Advanced Decision Support for Water and Environmental Systems, Univ. of Colorado	Water resource engineering

Areas of Focus

Within the existing mission described above, WWA shifts its specific research foci from year to year to stay current with stakeholder needs and emerging research frontiers. During the years of 2010-2016, WWA research and decision support products fell within one of several thematic categories that shifted through time:

- (1) Decision Support for the Colorado River Basin and Headwaters
Providing resource managers with the tools, data, and information about climate necessary to support management decisions in the Colorado River Basin and its headwaters region
- (2) Ecological Vulnerabilities, Impacts, and Adaptation
Assessing the ecological impacts of climate change and variability in Western landscapes and the resulting effects on water quality and quantity and other ecosystem services
- (3) Emerging Initiatives and Adaptation Strategies to Inform Climate Services
Responding to the needs of decision-makers to find productive strategies to adapt to both climate change and natural climate variability
- (4) Climate Vulnerability and Adaptive Capacity
Understanding how the region's changing exposure to climate affects the region's adaptive capacity
- (5) Extreme Events and Climate Risk Management
Leveraging understanding of past extremes and projected future extremes to better inform societal decision making in a changing climate
- (6) Designing Organizations and Networks for Usable Science
Building climate resilience across a variety of contexts through networks and organizations designed to produce usable science

Partners and Key Stakeholders

WWA engages with stakeholders at multiple levels within federal and state agencies, municipalities, universities and other organizations. Interactions with stakeholders vary from one-off phone calls for information to regular meetings to long-term projects in which WWA researchers and stakeholders work together to produce tools and reports. For much of the grant period, WWA had a Stakeholder Advisory Board (see Appendix B), which was a group of high-level decision makers and other partners who provide guidance on structuring our research agenda to best meet regional needs. In 2015, WWA changed to an External Advisory Board, which did not contain direct stakeholders but national and regional level thought leaders in climate adaptation and usable science. This change was made to help WWA gain an understanding of the bigger picture in terms of climate vulnerability and adaptation, and the state of usable science and co-production of knowledge across the United States.

Throughout this grant, WWA staff and researchers have worked with a very long list of stakeholders and partners, and it is not possible to list them all here. Table 2 provides a sample of some key organizations and agencies with which we worked closely over the last five years. We have done several projects with many of these organizations, and example projects are included in the table to give a flavor of the work done with stakeholders. We also worked with several other NOAA partners, including other RISA programs on climate and water issues as described below.

NOAA Partners

- Until 2013, WWA was physically housed in the **Physical Sciences Division (PSD)** of the NOAA Earth Systems Research Laboratory at the David Skaggs Research Center in Boulder, CO. This co-location provided frequent opportunities to interact with PSD researchers. In 2013, WWA moved onto the main campus of the University of Colorado and is housed within CIRES, a **NOAA Cooperative Institute**.
- WWA team members work extensively with staff at the **NOAA Colorado Basin River Forecast Center (CBRFC)** in Salt Lake City, and WWA Utah Liaisons Bardsley (until 2015) and Arens (current) are located in the CBRFC office. The Snowmelt Perturbations and Forecast Errors in the Upper Colorado River Basin project was developed largely to improve CBRFC forecasting.
- WWA collaborates with the **National Integrated Drought Information System (NIDIS)** on multiple efforts, including on Snowmelt Perturbations and Forecast Runoff Errors in the Upper Colorado River Basin, Climate Change Preparedness Among Tribal Communities in the American West, and on the Intermountain West Drought Early Warning System (DEWS) (formerly the Upper Colorado Basin DEWS).
- WWA staff members Udall and Bardsley were members of the Western Region Climate Science and Services Committee assembled by then-**NOAA Western Region Climate Services Director DeWayne Cecil**.
- WWA staff coordinate activities with **NOAA Central Region Climate Services Director Doug Kluck** and participated in the development of the Missouri River Basin Climate Consortium along with the North Central Climate Science Center.
- WWA staff member Elizabeth McNie worked with **NOAA Western Region Climate Services** staff to compile a database of climate service providers in the western United States.

Table 2. Key partners and stakeholders, 2010 - 2016

Organization	Relevant Project
Colorado Energy Office	<ul style="list-style-type: none"> • Colorado Climate Change Vulnerability Study • Colorado Climate Preparedness Project
Colorado River Water Conservation District	<ul style="list-style-type: none"> • Natural long-term variability of the Lower Colorado River basin using tree-ring estimates of past flows • Understanding snowmelt perturbations in the Upper CO River Basin
Colorado Water Conservation Board	<ul style="list-style-type: none"> • Climate Change in Colorado report
Denver Water	<ul style="list-style-type: none"> • Balancing severe decision conflicts under climate extremes in water management
DOE National Renewable Energy Lab	<ul style="list-style-type: none"> • Water, energy and climate change: freshwater use by power plants in the United States • Integrated water-energy modeling workshop • Support for climate adaptation plans at federal facilities
DOI North Central Climate Science Center	<ul style="list-style-type: none"> • WWA staff lead the climate science part of the overall strategy in building up the CSC • Built climate science into land and water conservation planning and decision-making in the American Southwest • Evaporation, drought and the water cycle across timescales • Evaluation of drought planning research on the Wind River Indian Reservation • Exploring Regional Climate Service Collaborations
National Integrated Drought Information System	<ul style="list-style-type: none"> • Evaluation of the Upper Colorado Drought Early Warning System
Navajo Nation	<ul style="list-style-type: none"> • Considerations for Climate Change & Variability Adaptation on the Navajo Nation
Southern Nevada Water Authority	<ul style="list-style-type: none"> • Cross-jurisdictional water marketing
The Nature Conservancy	<ul style="list-style-type: none"> • Built climate science into land and water conservation planning and decision-making in the American Southwest
Uinta-Wasatch-Cache and Ashley National Forests	<ul style="list-style-type: none"> • Climate vulnerability assessments and workshops
US Bureau of Reclamation	<ul style="list-style-type: none"> • UCAR COMET Program – climate training for water managers • Understanding snowmelt perturbations in the Upper CO River Basin • Framework for Colorado River water availability assessment • Colorado River Basin Water Supply and Demand Study • High-Resolution Meteorological and Hydrologic Data Extension to Trans-Boundary Basins in the Conterminous U.S., Southern Canada and Northern Mexico • Stochastic Streamflow Simulation at Interannual and Interdecadal Time Scales and Implications to Water Resources Management in the Colorado River Basin • Reconciling Projections of Future Flow in the Colorado River Basin • Informing the Responsible Use of Regional Climate Models by Stakeholders
USDA Northern Plains Regional Climate Hub	<ul style="list-style-type: none"> • Drought decision models for ranching • Exploring Regional Climate Service Collaborations
University of Utah Urban Planning	<ul style="list-style-type: none"> • Adaptation Guidance for Salt Lake City Department of Public Utilities
Utah Division of Water Resources	<ul style="list-style-type: none"> • Informing the Integration of Climate Information into Water Supply Planning in Various Contexts in Utah
Weber Basin Water Conservancy District	<ul style="list-style-type: none"> • Weber Basin Climate Sensitivity Analysis
Wasatch Area Dendrochronology Research (WADR) Group, Utah State University	<ul style="list-style-type: none"> • Real-time assessment of the development and use of stakeholder-oriented tree-ring paleohydrology research for water resource planning on the Wasatch Front

Cross-RISA Activities

- WWA researchers Averyt and Bardsley worked with **CLIMAS** to organize workshops aimed at improving CBRFC decision support tools for users.
- WWA researcher Lisa Dilling coordinated with M. Carmen-Lemos at **GLISA** and K. Dow at **CISA** to develop a comparative framework for analyzing stakeholder and science provider databases.
- The database developed by WWA for the Colorado Climate Preparedness Project has been shared with K. Ingram and others at **SECC**.
- **CLIMAS**, **CNAP**, and WWA co-convened a workshop on adaptive capacity in the Colorado River Basin, which will be hosted by WWA at the University of Colorado Boulder.
- WWA staff member Elizabeth McNie worked with Alison Meadow at **CLIMAS** and Tamara Wall at **CNAP** on building a database of climate service providers in the western US.
- Mark Shafer, a PI of **SCIPP**, is a member of our External Advisory Board.
- WWA staff have been working with **CLIMAS** on NIDIS' update of the Intermountain West Drought Early Warning System.

2010-2016 Program Highlights

Key Research Findings

- Dust deposition on snowpacks in the Upper Colorado River Basin ultimately reduces flow in the river by an average of 800,000 acre-feet per year, or five percent of the annual flow, according to research published in Proceedings of the National Academy of Sciences by WWA team members **Tom Painter, Jeff Deems, and Brad Udall**.
- Contrary to expectations, widespread tree mortality due to bark beetle infestations does not appear to result in major increases in nitrate levels in nearby streams, according to WWA researchers **James McCutchan and Suzanne Van Drunick** and their colleagues from the US Geological Survey and the US Forest Service.
- Wavelet spectral analyses of Colorado River Basin streamflow and climate data indicate that persistent, low-frequency variability in streamflow is a result of temperature fluctuations that modulate runoff efficiency, as found by WWA researchers **Ken Nowak, Balaji Rajagopalan, and Edith Zagana**.
- Working in southwestern Colorado, WWA researchers **Jason Neff, Karen Cozzetto, and Dan Fernandez** found that spatial variation in precipitation most strongly predicts vulnerability of vegetation to drought, followed by soil depth and soil texture. However, drought vulnerability also depends on the interactions between vegetation community type, soil depth and texture, and climate.
- WWA researcher **Joe Barsugli** found that the commonly used bias-correction method of quantile mapping itself may be biased, showing a wetter future in the Colorado River Basin than depicted by the underlying global climate model projections.
- Shifting Colorado River water storage to increase levels in Lake Powell relative to Lake Mead can increase overall system reliability in the face of flow reductions due to climate change, but doing so is contrary to current policy, according to WWA researchers **Balaji Rajagopalan and Andrew Verdin**.
- WWA researcher **Kristen Averyt** and her collaborators found that data on water withdrawals and consumption at power plants across the U.S. is significantly flawed, posing serious problems for water management.

- Among other major reforms, the Australian system of prioritization among water uses (critical human needs, then the environment, then all other uses) demonstrates one of the more significant policy and cultural differences in water management when comparing southeastern Australia's Murray-Darling Basin to the Colorado River Basin, according to WWA researcher **Brad Udall**.
- WWA researchers **Lisa Dilling** and **Kellie Archie** found that federal agency identification is more strongly correlated with public land managers' assessments of climate adaptation activities than are their individual beliefs or attitudes about climate change.
- An extensive assessment of user needs for modeled climate impacts on water quality by WWA researchers **Jimmy McCutchan** and **Mary Huisenga** indicates that stakeholders are concerned that regional climate and water quality models would be too complex and insensitive to site-specific factors to be used for making regulatory decisions.
- A study led in part by WWA researcher **James McCutchan** found that bark beetle infestations in Colorado have not led to significant increases in nitrate concentrations in nearby surface waters, contrary to expectations.
- Although certain renewable generation technologies (such as water-cooled concentrating solar power) use large amounts of water, overall low carbon energy penetration scenarios show the most substantial savings in water withdrawals and consumption at a national level, according to WWA researcher **Kristen Averyt** and her colleagues from the National Renewable Energy Laboratory and the Union of Concerned Scientists.
- Initial model results suggest that bark beetle infestations result in an increase in annual water yield on the order of approximately 3 to 15 percent over selected catchments across Colorado, according to sensitivity analyses by WWA's **Jeff Deems**, **Ben Livneh**, **Joe Barsugli**, **Noah Molotch**, **Carol Wessman**, and **Klaus Wolter**.
- WWA's **Lisa Dilling** and **Kristen Andersson** have found that although climate-related natural disasters can spur adaptation, there is often another explanation for a municipality undertaking adaptive action, such as the presence of a champion for the effort, the availability of additional financial resources, or opportunities for collaboration at other levels of government.
- With colleagues from the Salt Lake City Department of Public Utilities, the NOAA Colorado Basin River Forecast Center, and University of Utah, **Tim Bardsley** led the co-production of a study that found Salt Lake City's water supply could drop 1.8 to 6.5 percent for every degree Fahrenheit of warming in the region.
- While the September 2013 extreme rain and flood event along Colorado's Front Range was widely believed to be unprecedented, especially for the fall season, analysis by **Jeff Lukas**, **Joe Barsugli** and **Klaus Wolter**, with colleagues at NOAA Earth Systems Research Laboratory showed that a September 1938 event had an eerily similar synoptic pattern, and similar results in terms of precipitation totals and flooding impacts on the Front Range.
- Winter temperatures in the Rocky Mountains are projected to warm more in the future than lower-elevation regions at the same latitude, according to an analysis of CMIP5 global climate model runs by **Imtiaz Rangwala** and colleagues at Rutgers University.
- The worst watershed stresses seen across the country between 1999 and 2007 could become the new normal under a warming climate, according to research by **Kristen Averyt** and **James Meldrum**, along with colleagues from the USDA, Tufts University, and the Union of Concerned Scientists.
- Future projected changes in temperature and precipitation could exacerbate the effects of dust deposition on snowpack in the Upper Colorado River Basin, inducing additional losses of 10 to

20% of flow and earlier runoff timing shifts of 10-20 days relative to current climate and moderate dust conditions, according to research by **Jeff Deems** and **Joe Barsugli**.

- Water resources decision makers seeking to respond to climate variability and change need far more than additional information, according to a new paper authored by WWA's **Lisa Dilling** and **John Berggren** along with colleagues from the Carolinas Integrated Sciences and Assessments (CISA) and the Great Lakes Integrated Sciences and Assessments (GLISA). Governance arrangements and collaboration—so-called “enabling factors”—are often as important as the information itself, a finding with major implications for the provision of regional climate services.
- Under a high emissions scenario (RCP 8.5), Colorado is expected to warm 3.5-6.5°F by the middle of the 21st century, according to the updated *Climate Change in Colorado* report authored by WWA's **Jeff Lukas**, **Joe Barsugli**, **Imtiaz Rangwala** and **Klaus Wolter**, along with affiliate Nolan Doesken from the Colorado Climate Center. Among the expected impacts of this warming are hotter summers and wetter winters.
- Colorado faces a number of key vulnerabilities in a warmer future, according to the *Colorado Climate Change Vulnerability Study* co-edited by WWA's **Eric Gordon**. Particularly vulnerable entities include water supply entities with junior water rights and little storage, residences and other buildings in floodplains, the wildland-urban interface, and those exposed to high daytime temperatures and West Nile Virus.
- WWA's **Lisa Dilling**, **Bill Travis** and **Roberta Klein**, along with other colleagues, contend that addressing so-called “adaptation deficits” and focusing on the implementation of no-regrets strategies may be insufficient for climate change adaptation. Their review and synthesis of research from the climate adaptation and natural hazards fields indicates that the dynamics of vulnerability dictate that decision makers need to consider how choices in one part of a system can affect outcomes in another.
- A comprehensive high-resolution simulation of catchment-scale water yield changes from land cover disturbances indicates that annual water yield can increase between 8 and 13 percent from bark beetle infestations, according to results in a recently published paper by an interdisciplinary team of WWA researchers including **Ben Livneh**, **Jeff Deems**, **Brian Buma**, **Joe Barsugli**, **Dominik Schneider**, **Noah Molotch**, **Klaus Wolter**, and **Carol Wessman**. Desert dust deposition in the same catchments causes snowmelt to occur earlier, but the two disturbances appear to have little interactive effects. These findings that are being used in experimental adjustments to Colorado Basin River Forecast Center streamflow forecasts.

Key Accomplishments and Outreach

New Intermountain West Climate Dashboard

PIs: Jeff Lukas, Klaus Wolter, Eric Gordon, Tim Bardsley

Stakeholders/Partners: Water managers and others responsible for climate-sensitive resources

Leveraged Funding: In-kind contribution from NOAA ESRL Physical Sciences Division

For several years, Western Water Assessment produced the *Intermountain West Climate Summary* (IWCS), a semi-monthly update of climate and hydrology in Colorado, Wyoming, and Utah. In the interests of providing more up-to-date information in a clearer format for a variety of stakeholders, WWA's Jeff Lukas led an effort to implement the Intermountain West Climate Dashboard (available at <http://www.colorado.edu/climate/dashboard.html>). Based on a prototype for the Missouri River Basin developed at the NOAA Earth System Research Laboratory's Physical Sciences Division, the Dashboard contains an array of many of the same climate information graphics as in the IWCS, but directly feeds them from their original providers (such as NOAA CPC) to automatically update as often as those providers update them. Clicking on the thumbnail of each graphic brings up a full-sized version on the same page. In order to provide additional context and analysis, WWA staff also write and post bimonthly briefings on the Dashboard to provide additional context and analysis.

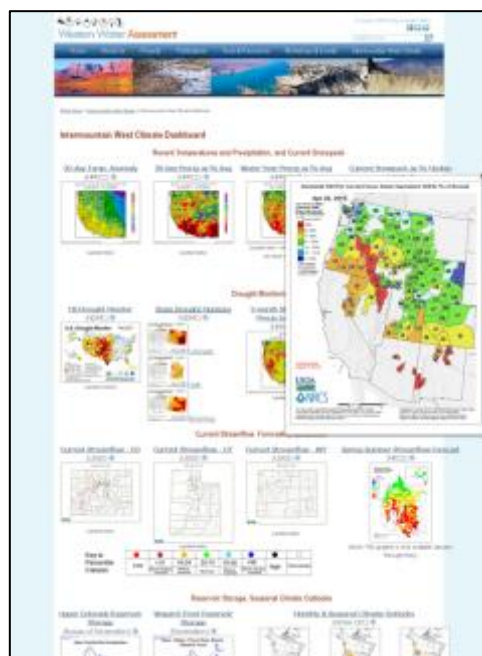


Figure 1. A portion of WWA's Intermountain West Climate Dashboard, available at <http://www.colorado.edu/climate/dashboard.html>.

WWA and NIDIS Produce 2012 Drought Briefing

PIs: Jeff Lukas, Lisa Darby (NIDIS)

Stakeholders/Partners: NIDIS; various water and resource managers across the West

WWA worked in collaboration with the National Integrated Drought Information System (NIDIS) to develop a [two-page briefing document](#) focusing on the severe drought conditions that emerged in 2012 in Colorado, Utah, and Wyoming. In addition to reporting drought conditions, the special issue compared conditions in 2012 to 2002, considered a benchmark drought year throughout the Intermountain West. The briefing was intended for consumption by higher-level decisionmakers, along the lines of the west-wide "Quarterly Climate Impacts and Outlook" document crafted by NOAA, NIDIS, and the Western Governors' Association. A special issue of the Intermountain West Climate Summary (http://www.colorado.edu/climate/iwcs/2012_July.html) supplemented the two-page briefing by providing additional analyses and information graphics for the 2012 drought.

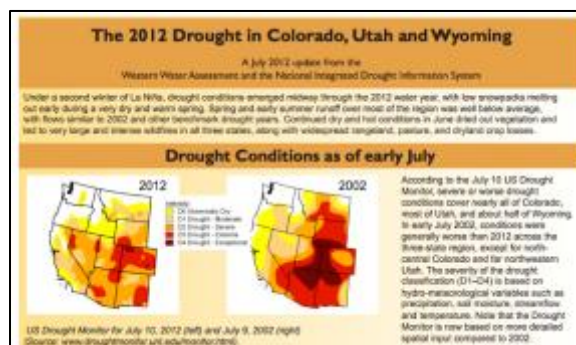


Figure 2. WWA and NIDIS co-produced a drought briefing comparing climate conditions in 2012 with 2002, another significant drought year for the Intermountain West.

Conceptual Model on Beetle Infestation Impacts to Hydrology

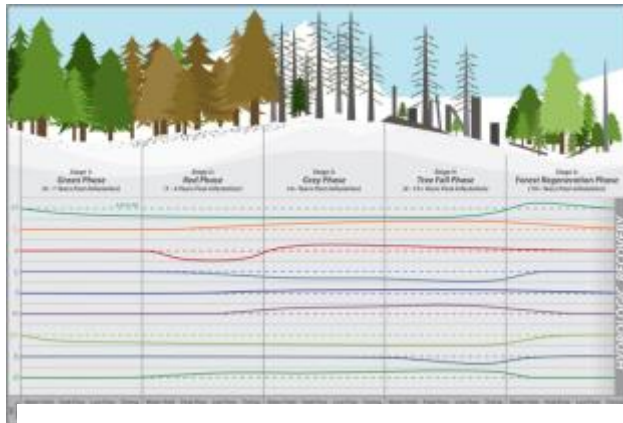


Figure 3. Conceptual model outlining impacts of bark beetle infestations on various hydrologic processes. Reproduced from Pugh and Gordon (2012).

PIs: Eric Gordon, Evan Pugh (CU Geology), Jeff Lukas

Stakeholders/Partners: US Forest Service Rocky Mountain Research Station; various water and land managers across Intermountain West

Under the “Beetles, Forest Change, and Water” project, WWA has engaged with a diverse group of stakeholders and researchers dealing with the ongoing bark beetle epidemic, with the aim of developing integrated, decision-oriented information that can help stakeholders understand and plan for potential impacts on water resources. As part of that effort, WWA’s Eric Gordon worked with Evan Pugh of the University of Colorado Department of Geological

Sciences to develop a conceptual model that synthesizes research examining bark beetle impacts on individual ecohydrological processes (see Fig. 4). The model was published in *Hydrological Processes* in 2012 (Pugh and Gordon 2012) and has been used at multiple WWA workshops on beetle infestation impacts to water supplies.

Resource Manager Workshop on Bark Beetle Impacts to Water Supplies

PIs: Eric Gordon, Jeff Lukas, Tim Bardsley

Stakeholders/Partners: US Forest Service Rocky Mountain Research Station; US Forest Service Region 4; Colorado Basin River Forecast Center; water and forest managers in Utah
Leveraged Funding: In-kind contribution from US Forest Service

Bark beetles have impacted more than 4 million acres of forest in Colorado and more than 5 million acres across Utah. Water and forest managers alike are concerned about potential impacts on hydrology and water quality from such widespread

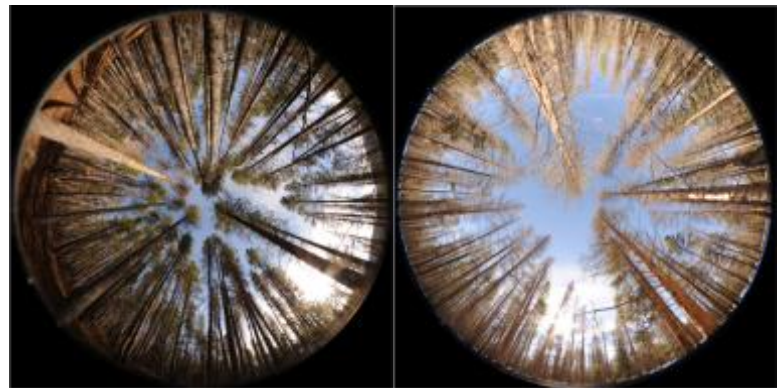


Figure 4. Hemispherical photos of living (left) and grey-phase beetle-killed lodgepole pine trees in northern Colorado. Grey-phase trees intercept significantly less snow, resulting in increased accumulation at the surface. Photos courtesy of Evan Pugh.

vegetation mortality in high-elevation watersheds. Building on the results of two previous WWA symposia organized to help researchers understand the state of the science on this issue, WWA held its first explicitly manager-oriented workshop on beetles and water on December 1st in Salt Lake City. Nearly 40 water and forest managers attended in person, with approximately 70 others watching via real-time webcast (webcast archive is accessible on the event webpage at <http://wwa.colorado.edu/ecology/beetle/mpbUTworkshopDec2011.html>). In addition, pre- and post-workshop surveys helped WWA researchers better understand how to successfully communicate complex and uncertain scientific information on the topic to different audiences.

Native Communities and Climate Change Database



Figure 5. Native Communities and Climate Change web portal available at <http://www.tribesandclimatechange.org>.

PIs: Karen Cozzetto, Julie Teel-Simmonds, Julie Nania
Stakeholders/Partners: Natural Resources Law Center, Navajo Nation, Ute Mountain Ute Tribe, other native communities

Leveraged Funding: \$45,000 from NIDIS

WWA researchers have developed an online database containing numerous resources on the impacts of climate change on American Indian tribes, on tribal adaptation activities and planning efforts, and on relevant federal laws and policies that support or inhibit these efforts. As part of the effort, the team developed outreach materials describing

the database and presented it at multiple forums, including the National Congress of American Indians 2011 Mid-Year Conference and the Northern Arizona University Institute for Tribal Environmental Professionals' Climate Change Training. In addition, a memo on the database was developed and submitted as a technical input the National Climate Assessment.

Modeling Climate-Driven Water Quality Changes on Colorado's Plains Rivers

PIs: James McCutchan, Suzanne van Drunick
Stakeholders/Partners: Colorado Department of Public Health and Environment; water utilities; wastewater treatment operators

In order to better understand drivers of pH variation and other water quality variables, WWA researchers conducted field measurements of algal biomass in rivers along Colorado's plains and built a neural network model to understand the relationships among multiple drivers of water quality, including climate change. Preliminary results indicated that continued warming could lead to higher pH levels and, in turn, greater levels of organic matter such as algae, posing challenges for wastewater treatment plant operators seeking to remove organic matter from effluent. However, hydrologic changes from drought water management were found to be more important drivers of periphyton biomass on streambeds and associated pH levels than water temperatures alone, demonstrating that impacts of climate warming are merely one in a set of multiple stressors on aquatic ecosystems and water supplies.

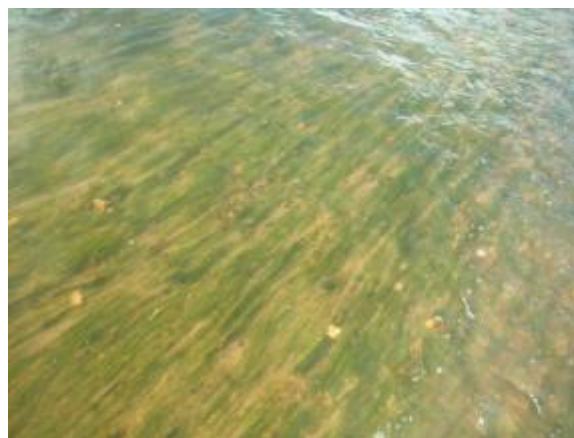


Figure 6. High biomass of attached algae typical of rivers on Colorado's plains after periods of extended low discharge. Photo courtesy James McCutchan.

Drought Adaptation Among Ranchers in the Intermountain West



Figure 7. Cows grazing on a ranch in Moffat County, Colorado. Photo courtesy Kristin Gangwer.

PIs: William Travis, Kristin Gangwer

Stakeholders/Partners: National Integrated Drought Information System (NIDIS); ranchers

Drought imposes physical, social, and economic impacts on ranching systems in the Rocky Mountains. To better understand how ranchers cope with drought, WWA Graduate Research Assistant Kristin Gangwer conducted interviews in the “Three Corners” region where Colorado, Wyoming, and Utah intersect. In this dry, sparsely populated region, ranchers use a range of strategies for buffering against, coping with, and adapting to the various impacts of drought.

Gangwer’s findings, documented in a completed master’s thesis, demonstrate that ranchers’ operations are comprised of varying quantities of

private, privately leased, state, and federal land – and with each of these forms of tenure come different levels of oversight on management during drought. For the ranchers interviewed, the complex land tenure system appears to support their drought coping and buffering strategies. It proves to be a constraint, though, in implementing long-term adaptation to drought and general aridity, particularly due to range improvement policies and tenure insecurity.

Colorado Climate Preparedness Project

PIs: Roberta Klein, Eric Gordon, William Travis, Brad Udall, Kristen Averyt, Jeff Lukas

Stakeholders/Partners: Colorado Governor’s Energy Office, Colorado Water Conservation Board, Colorado Department of Agriculture
Leveraged Funding: \$161,000 from State of Colorado

At the request of the state of Colorado, WWA researchers Roberta Klein, Eric Gordon, Kristen Averyt, Brad Udall, Jeff Lukas, and William Travis conducted a survey of climate impacts and adaptation options in five sectors—water; electricity; wildlife, ecosystems, and forests; agriculture; and outdoor recreation. The results of this effort are compiled in a database (<http://www.coloadaptationprofile.org>) and a final report presented to Governor Hickenlooper and his staff (http://www.colorado.edu/CCPP_report.pdf). The report and the database are intended to help facilitate future vulnerability assessment and adaptation planning efforts across the state. This work is also intended to contribute to the National Climate Assessment.



Figure 8. Colorado Climate Preparedness Project database.

Workshop to Improve NOAA NWS RFC Decision-Support Tools



Figure 9. CBRFC Water Resources Outlook Tool.

PIs: Kristen Averyt, Tim Bardsley, Gigi Owen (CLIMAS)

Stakeholders/Partners: NOAA NWS Colorado Basin River Forecast Center

Leveraged Funding: In-kind support from CBRFC

WWA researcher Averyt, working with others from the Climate Assessment for the Southwest (CLIMAS) and the NWS Colorado Basin River Forecast Center (CBRFC), collaborated on a stakeholder workshop held in Grand Junction, Colorado in April 2010 that focused on a new CBRFC decision-support tool. The workshop engaged participants with computer-based training exercises and scenario games to provide the CBRFC developers with focused feedback to improve the tool. After the success in Colorado, similar workshops

are being scoped for 2011 for Utah, Oklahoma, and Georgia.

Integrated Water-Energy Modeling Workshop

PI: Kristen Averyt

Stakeholders/Partners: National Renewable Energy Laboratory (NREL); Union of Concerned Scientists (UCS)

Leveraged Funding: \$100,000 from UCS

In August 2010, WWA hosted a workshop at NOAA entitled “Integrated Water-Energy Modeling Efforts & Reconciling Water Requirements for Electricity Generation.” The results of the meeting were presented at the American Geophysical Union 2010 Fall Meeting. The consensus around the water requirements for energy (which leveraged WWA efforts to improve the University of California-Santa Barbara’s database) is reflected in an NREL report released in April 2011. At the workshop, our parallel effort with NREL was recognized and subsequently merged into a single effort led by NREL. Averyt will be working with the Union of Concerned Scientists to host a meeting with a similar theme, but focused on the collaboration with UCS, in late Summer 2011.



Figure 10. Valmont power plant, Boulder, Colorado. Photo courtesy Let Ideas Compete.

Drought Impact and Vulnerability Indicator Suite

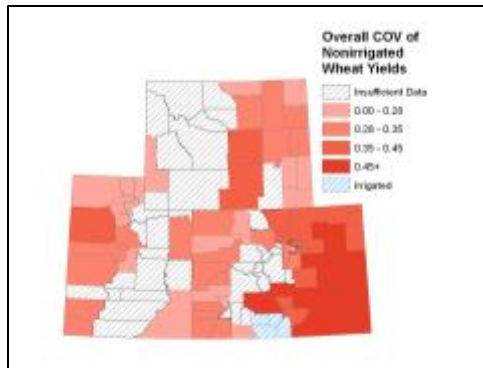


Figure 11. An indicator of drought sensitivity in agriculture: Dryland wheat yield variability measured as the coefficient of variation (standard deviation divided by the mean). 1970-2009.

PIs: William Travis, Kristin Gangwer, Roberta Klein
Stakeholders/Partners: National Integrated Drought Information System (NIDIS)

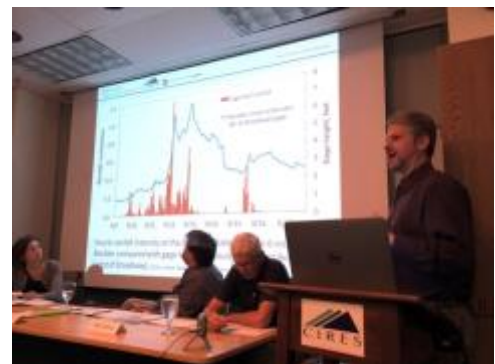
In 2010, WWA researchers worked to meet a recommendation by NOAA's 2009 Social Science Working Group for improved measures of socioeconomic impacts and better indicators of societal vulnerability to atmospheric hazards. Travis and Gangwer assembled a set of agricultural, water supply, and ecological indicators of drought effects that go beyond precipitation, snowpack and runoff measures.

Included in the initial roster are indicators such as inter-annual crop yield variation (Figure 4), abandoned cropland, agricultural disaster declarations, number of declared water shortages among a sample of small to medium size municipal

supply systems, and wildfire area. The next step is to fashion the indicators into a "drought dashboard" capable of reflecting impacts of drought in real-time.

Rapid Response to Colorado Front Range Flooding

In the wake of historic flooding across Colorado's Front Range, **Jeff Lukas** led the development of a four-page assessment report and a widely attended public briefing (Figure 1) discussing the meteorological, climatic, and hydrologic context of this extreme event. Nearly 100 people in-person and over 200 online attended the briefing, which also featured **Klaus Wolter** along with Martin Hoerling and Kelly Mahoney of the NOAA Earth Systems Research Laboratory's Physical Sciences Division and Nolan Doesken of the Colorado Climate Center at Colorado State University.



Informing Water Managers About New Climate Projections

Imtiaz Rangwala has done extensive analysis of the differences between the projected climate in the Coupled Model Intercomparison Project, Phase 3 (CMIP3) and the newer set of model runs (CMIP5) for the Upper Colorado River Basin and the state of Colorado. Selected results of this analysis were presented at a variety of stakeholder forums, including the Upper Colorado River Basin Water Conference in November 2013, during a webinar held by the Carpe Diem West Academy, and at a WWA-organized meeting of the Front Range Climate Change Group (see below). Of particular interest to water management stakeholders were changes in projections of future precipitation in basins in western Colorado that feed into the Colorado River.

Media and Stakeholder Outreach on the Energy-Water Nexus

In addition to publishing several academic papers on the topic, **Kristen Averyt** engaged both decision makers and the public in numerous efforts intended to promote understanding of the effects of energy production on water supplies. These efforts included filming a [video](#) with the University of Colorado Boulder's Office for University Outreach, being [interviewed on Colorado Public Radio](#), and co-presenting a [webinar](#) hosted by the Association of Metropolitan Water Agencies.

Describing Research Results to Utility CFOs

In March 2014, **Doug Kenney** co-hosted a workshop of water utility Chief Financial Officers (and related staff) examining water utility revenue volatility associated with climate events and other stressors affecting water demand and deliveries. This “CFO Connect Water Utilities” was held in cooperation with Ceres and the Water Efficiency Foundation and incorporated information from Kenney’s 2014 paper in the *Journal of the American Water Works Association* entitled “Understanding Utility Disincentives to Water Conservation as a Means of Adapting to Climate Change Pressures.”

Promoting Literacy Across Climate Topics

Eric Gordon, Jeff Lukas, Imtiaz Rangwala, Joe Barsugli, Lisa Dilling, and Kristen Averyt convened a series of climate literacy workshops for the Front Range Climate Change Group, an informal gathering of municipal water utility managers from Colorado’s Front Range. Topics covered included updated (CMIP5) projections of precipitation in the Upper Colorado River Basin and relevant uncertainties, the effects of wildfire on soils and erosion into reservoirs, and communication of climate change information to the public.

Outreach for *Climate Change in Colorado*



Figure 12. WWA’s Jeff Lukas at the Colorado Water Congress Annual Meeting in Centennial, CO, January 2015.

Working directly with the Colorado Water Conservation Board, WWA comprehensively updated its 2008 [Climate Change in Colorado](#) report. This report is an authoritative assessment of the physical science regarding observed and projected changes in the state’s climate and is being used to inform water supply planning. Since its publication in August 2014, WWA’s **Jeff Lukas** has given over a dozen presentations on the report to stakeholder audiences, including the American Water Resources Association Colorado Section, the Colorado Water Congress, the Colorado Groundwater Conference, the Colorado Foundation for Water Education’s Climate and Water Workshop, the Front Range Climate Change Group, and the Federal

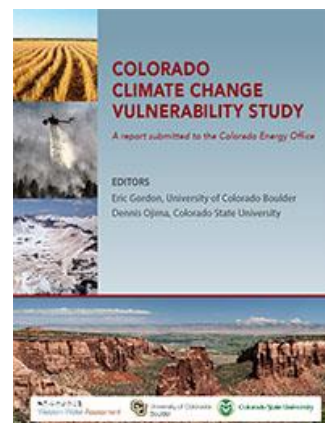
Emergency Management Agency’s Colorado Climate Change Preparedness and Resilience Workshop. In addition, Jeff was invited to speak at “NCAR Ignite” at the National Center for Atmospheric Research, and gave a 5-minute presentation on Colorado’s water and climate in [Dr. Seuss-style rhyme](#).

Preparation for White House-FEMA Colorado Climate Preparedness and Resilience Workshop

As part of a major climate-resilience initiative, the White House (CEQ, OSTP, and National Security Staff) and FEMA conducted three pilot workshops nationwide in fall 2014. One took place in Fort Collins, Colorado, gathering 80 local, state, and federal officials, resource and hazard managers, and content experts. WWA’s **Jeff Lukas** assisted in the workshop preparation and execution by drafting text for the workshop brochure, reviewing the premises of the drought scenario for the ‘tabletop exercise’; and presenting on projected climate impacts in Colorado at the workshop.

Media Response to the *Colorado Climate Change Vulnerability Study*

In early 2015, WWA, along with colleagues at Colorado State University, released the [Colorado Climate Change Vulnerability Study](#), an overview of key climate change vulnerabilities across the state. Drawing from existing data and peer-reviewed research, the study summarizes the key challenges facing seven sectors: ecosystems, water, agriculture, energy, transportation, outdoor recreation and tourism, and public health. Upon release of the report, WWA's **Eric Gordon** was featured on a variety of media outlets, including ClimateWire, Colorado Public Radio, the Denver Post, KOA Radio 850AM, and KGNU radio. In addition, Gordon presented findings from the study at venues including the American Water Resources Association Colorado Section meeting, the Colorado Homeland Security Advisory Committee, and the Denver Foundation's Environmental Affinity Group.



Water in the Western US Massive Open Online Course



In April 2015, WWA's **Eric Gordon** and Anne Gold from CIRES Education and Outreach co-taught a Massive Open Online Course (MOOC) entitled "[Water in the Western United States](#)." Available on the Coursera platform and free to anyone with an Internet connection, the course was designed as an undergraduate-level survey and featured 17 expert guest lecturers, including WWA's **Jeff Lukas**, **Ben Livneh**, and **Kristen Averyt**. More than 6,000 students registered for the course, including a number of existing WWA stakeholders. The course was a novel opportunity for WWA and a foray into new education venues. The professionally edited video lectures on water and climate will also be useful in future WWA outreach activities.

Business for Social Responsibility (BSR) Climate Science Initiative Webinar

WWA's **Kristen Averyt** and **Eric Gordon** provided a webinar briefing in April 2014 to the BSR Climate Initiative. BSR is a nonprofit focused on promoting sustainability among some of the world's largest companies, and their Climate Science Initiative includes representatives from BNP Paribas S.A., The Gap Inc., Lockheed Martin Corporation, Standard Chartered PLC, and Unilever PLC. Kristen spoke about the effects of climate change on water resources globally and nationally, while Eric provided perspective on Colorado's efforts to prepare for climate impacts to water supplies based on the [Colorado Climate Change Vulnerability Study](#).

Appendix A: Select Papers and Reports

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Appendix B: WWA Advisory Boards

WWA Stakeholder Advisory Board Members, 2010 - 2015

Curtis Brown	Director, Research & Development, Science & Technology Division, US Bureau of Reclamation
Terrance Fulp	Deputy Regional Director, Lower Colorado Region, US Bureau of Reclamation
Jennifer Gimbel	Director, Colorado Water Conservation Board
Melinda Kassen	Independent environmental consultant
Eric Kuhn	General Manager, Colorado River Water Conservation District
Chuck Kutscher	Principal Engineer, National Renewable Energy Laboratory, Department of Energy
Patricia Mulroy	General Manager, Southern Nevada Water Authority
William Neff	Director, Physical Science Division, NOAA Earth System Research Laboratory
Michelle Schmidt	Hydrologist-in-Charge, NOAA NWS Colorado Basin River Forecast Center
James Verdin	Deputy Director, National Integrated Drought Information System (NIDIS), USGS
Marc Waage	Manager, Water Resources Planning Division, Denver Water
Robert Wigington	Western Water Policy Counsel, The Nature Conservancy

WWA External Advisory Board Members, 2015 - present

Kathy Jacobs (chair)	Director, Center for Climate Adaptation Science and Solutions, University of Arizona
Justin Derner	Director, USDA Northern Plains Regional Climate Hub
Randall Dole	Senior Scientist, Physical Sciences Division, ESRL, NOAA
James Ehleringer	Distinguished Professor, Biology, University of Utah
Richard Moss	Senior Staff Scientist, Joint Global Change Research Institute, PNNL, University of Maryland
Mark Shafer	Associate State Climatologist, University of Oklahoma and PI of SCIPP RISA
Amy Snover	Assistant Dean for Applied Research, College of the Environment, University of Washington